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Presence, *Vol. 7, No. 3, June 1998*, 278–289

Evaluation of the Effects of a Head-mounted Display on Ocular Accommodation

Abstract

We evaluated a commercially produced head-mounted display (HMD) to determine its short-term effects on human ocular accommodation. Thirteen subjects (seven men and six women, ranging from 13 to 44 years old) were tested for changes in a number of parameters before and after viewing a full-length movie (approximately two hours) on a HMD. As a control, subjects were also tested before and after viewing a movie on a high-quality NTSC color television, and also before and after a one-hour intermission. Accommodation dynamics and range were measured. Data showed well-known trends due to subject age. Only one statistically significant change was found: a slight increase in the latency of relaxation accommodation after HMD viewing.

1 Introduction

1.1 Head-mounted Displays

As head-mounted displays (HMDs) become commercialized for virtual reality and personal video uses, there is some concern that their use for several hours at a stretch will cause visual adaptation effects that may disturb normal vision for some time after the actual HMD use, perhaps making tasks such as driving more hazardous. The literature on oculomotor systems points to a number of potential problems, particularly regarding the interaction between the convergence control system and the accommodation system, and the adaptation of oculomotor control system to HMD viewing conditions and their subsequent re-adaptation to real-world viewing. Ebenholtz (Ebenholtz, 1991) discusses some of the potential problems with special attention to adaptation. Robinett (Robinett & Rolland, 1992) and Liu (Liu et al., 1993) discussed visual problems inherent in the design of stereoscopic displays. Hiruma and Fukuda (Hiruma & Fukuda, 1993) measured subjects' accommodation when viewing binocular, stereoscopic TV images and found that convergence accommodation could add or subtract as much as 0.2 diopters to the accommodative response during viewing.

Only a few studies have been undertaken in which the effects of HMD use have been directly measured. Mon-Williams (Mon-Williams et al., 1993) tested the phorias and distance vision of subjects using an early commercial HMD and reported changes in some subjects after only ten minutes of use; Rushton, Mon-Williams, and Wann (Rushton et al., 1994) repeated their experiments on another model of biocular HMD and found no changes.

1.2 Ocular Accommodation

1.2.1 Anatomy and Physiology of Ocular Accommodation. Accommodation refers to the eye's ability to focus at different distances. The mechanisms of human accommodation, as we understand it today, was first described by Helmholtz and is called the *dual/active/indirect* theory of accommodation. Human accommodation is accomplished by changing the shape of the lens, primarily the anterior surface of the lens; this is effected by changing the amount of tension on the lens capsule with the ciliary muscle (the lenticular and extralenticular components, hence *dual*). The lens is something like a clear, hemispherical capsule filled with fluid (actually elongated elastic cells), with the less-curved anterior surface especially increasing its curvature. If the lens is under no external stress, it rounds out like a bubble, increasing the power of the lens and focusing on nearer rather than farther objects. Attached to the equator of the lens is a system of very thin fibers called the zonules of Zinn by which the lens is suspended in the eye. The other ends of these zonules—peripheral zonules—are anchored in the eye at the pars plana and terminate at the ora serrata. These zonules exert a passive tension on the lens equator, pulling on and stretching the lens capsule and flattening the lens. The ciliary muscle is the active component in accommodation; it is an annulus of chordal-oriented muscle whose inner diameter takes origin at the scleral spur, a ring of strong tissue located at the conjunction of the cornea and the sclera. The outer diameter is inserted into the zonules (in Bruch's membrane) so that when the muscle contracts (hence *active*), it pulls with the lens capsule against the peripheral zonules, reducing the tension first on the axial portion of the zonule and then on the lens capsule (thus *indirect*) and allowing the front of the lens to increase in curvature. The difference in refractive power between the lens with no ciliary muscle contraction (far point) and maximum ciliary muscle contraction (near point) is the range of accommodation. The lens changes with age, thickening, becoming less dense and hence less refractive, but also becoming more curved on the anterior surface (Brown, 1974; Koretz et al., 1984). The decrease in refractive index tends to decrease the power of the lens (making it more hyperopic) while the increase in curvature tends to increase its power (making it more myopic): the former process usually dominates. The range of accommodation decreases with age as a result of the thickening of the lens and the stiffening of the lens capsule, until there is essentially no accommodation left.

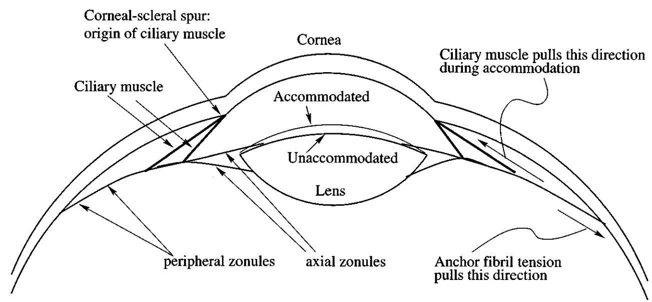


Figure 1. *Mechanism of accommodation*

1.2.2 Tonic Accommodation. It was observed during the 1940s that when subjects were viewing an empty field, or ganzfeld, that their level of accommodation did not relax to their far point but tended to be between 1 and 3 diopters. Thus, rather than relaxing completely, ciliary muscle maintains a certain degree of contraction, called ''tonic accommodation'' or ''dark focus'' (Campbell, 1954; Campbell and Westeimer, 1959) and manifests itself as night myopia (Heath, 1956) at scotopic light levels, or space myopia when no focusable image is present. Space myopia was described by Whiteside (Whiteside, 1957) and has been shown to decrease visual detection capabilities in pilots. A distance target seen through a positive lens near the eye will be blurred and unfocusable, or ''fogged.'' If slightly fogged, such a stimulus tends to cause the accommodation to relax toward its far point, because any accommodation will make an already blurry image worse. (If the image is extremely fogged it approximates a ganzfeld, and the above discussion of tonic accommodation applies.)

1.2.3 Instrument Myopia. When individuals use an optical instrument, like a microscope, that can be adjusted for accommodative demand, they often adjust it not for the most relaxed accommodative distance—their far point—but for a near point to which they have to accommodate; this is called ''instrument myopia.'' This choice of adjustment increases demand on ciliary muscle force and can increase the level of accommodative fatigue for people who, for example, must peer into microscopes all day. It is foreseeable that people may tend to adjust HMDs the same way, with similar results.

1.2.4 Accommodation and Convergence. The accommodation system is part of the near triad, a system of communicating control systems in the brain that control pupillary constriction, accommodation, and binocular convergence. Normal vision is binocular, and near targets can be converged upon by both eyes very accurately. The convergence system can drive accommodation; indeed, this is the primary method of accommodation for normal vision. Fatigue in the convergence system can influence accommodative response, and the convergence system is by far the easiest eye movement system to fatigue (Stark, 1984). Interestingly, it is also much less robust to drugs (Rashbass and Westheimer, 1961); thus, the familiar phenomenon of double-vision as a primary sign of ethanol intoxication.

1.3 Aim

In this study, we investigated the possible short-term effects of HMD use on the human accommodation system. Subjects viewed a full-length movie (approximately two hours long) with an HMD commercially produced by Sony Corporation. To control for errors, we compared the measurements to two different controls: measurements were made before and after viewing a movie on a large-screen television, and measurements were made before and after a one-hour break for lunch.

2 Methods

2.1 Subject Demographics

Twenty-one subjects were recruited (with monetary compensation) for the full study to form a diverse group of unpracticed subjects (such as one would find, for example, as passengers in a transpacific airplane) with a wide age range (13–58 years). Eight of the subjects had insufficient accommodative response to be included in the dynamic accommodation portion of the study. Of the thirteen remaining subjects, six were under age thirty, five were between thirty and forty years, and two were over forty; there were seven men and six women; nine were from various parts of the United States, two were Swiss, one was Italian, and one was from New Zealand.

2.2 Viewing Protocol

Testing was done before and after viewing the movie with the HMD, and each testing period lasted approximately one hour. As an internal comparison, the subjects were also tested before and after viewing a full-length movie on a color television from a distance of eight feet. Prior to testing, subject demographics and the subject's medical history specifically related to vision were recorded. After each movie-viewing period, subjects' comments and preferences were recorded.

Each subject reported to the laboratory at 8:30 A.M. on their testing day. The subject was introduced to the experimenters and the day's schedule was explained, after which demographic information and relevant medical history was taken. From 9:00 A.M. until 10:00 A.M. (*Pre-test 1*), the clinical and laboratory measurements were made. From 10:00 A.M. until approximately 12:00 P.M. (*Movie 1*), the subject watched the first movie on either the HMD or the television. Clinical and laboratory measurements were then made immediately after the end of the Movie 1 (*Post-test 1*), from approximately 12:00 P.M. to 1:00 P.M. From 1:00 P.M. until about 2:00 P.M. the subject had a lunch break. From 2:00 P.M. until 3:00 P.M. the subject was again tested (*Pre-test 2*); from 3:00 P.M. until 5:00 P.M. the subject viewed another movie on the other display (i.e., the HMD if the first movie was viewed on the television); the final round of testing (*Post-test 2*) was started when the first movie ended at roughly 5:00 P.M. and lasted, like the other three rounds, for about one hour.

Two subjects were run each day. During the testing periods, one subject would be undergoing the eye-movement and driving simulation tests while the other was undergoing dynamic accommodation and clinical tests (although only the dynamic accommodation results are discussed in this paper). The order of movie-viewing displays was chosen randomly for one of each day's pair of subjects.

The HMD used was a two-screen, biocular prototype from the Sony Corporation. The field of view of the display was approximately 24 degrees. The resolution of the displays was 300 × 340 pixels. The display position could be laterally and independently adjusted for each eye, and was adjusted by the subject with the help of experimenter for comfortable viewing. The subject viewed the movie while sitting in a reclining chair; subjects wore their normal corrective lenses. The color television display was a Sony Trinitron, 27-inch, Model KV-27TS32. The subject viewed the movie from a large overstuffed chair at a distance of 8 feet (2.4 meters). The field of view was approximately 16.3 degrees.

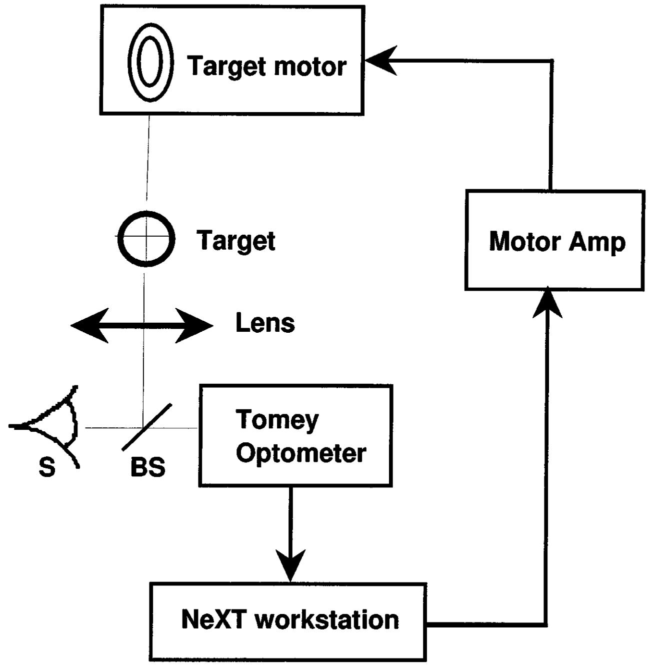


Figure 2. *Experimental Setup*

2.3 Dynamic Accommodation Measurements

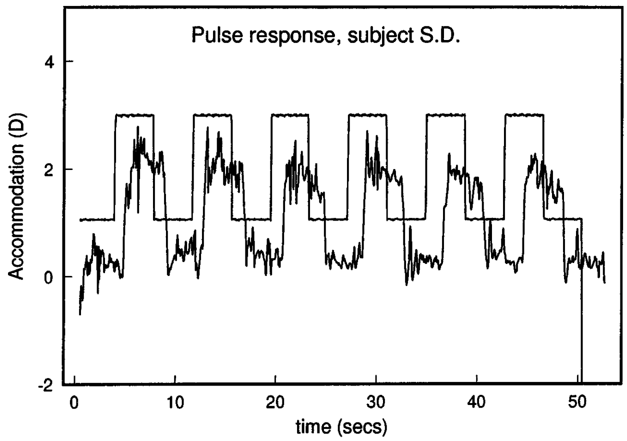
The stimulus protocols were chosen to reveal changes to accommodation response that could be a result of accommodative fatigue or adaptation. The subject views with monocular vision a target that changes optical distance over time, and his or her dynamic accommodative response is recorded. The optical system is designed so that the only stimulus to accommodation is target light vergence, and all other cues to target distance, such as retinal disparity, motion parallax, or off-axis target movement, are eliminated or minimized.

The signal characteristics of the accommodative response measurements taken during the four test periods were compared to evaluate possible short-term accommodation changes, such as fatigue, instrument myopia, or reduction of accommodative range.

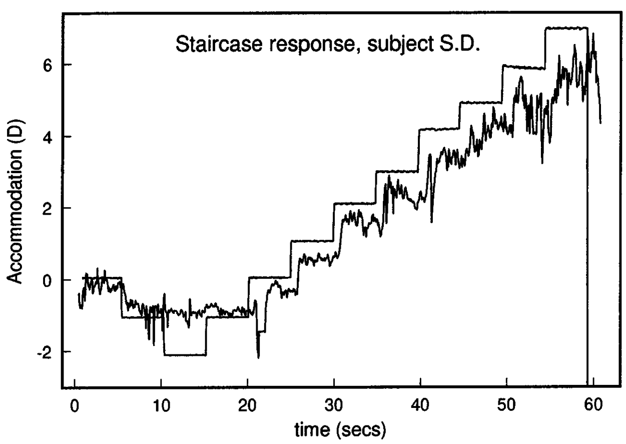
Measurement Technique. The target was presented monocularly to the subject with a +10.0 D Badal lens system (Badal, 1876) capable of positioning the target at optical distances from +3.0 diopters to −7.5 diopters (a target at infinity has 0 diopters of vergence; light from near objects in the real world have negative vergence; a target with a positive dioptric value is ''beyond infinity'' and cannot be focused except by hyperopes). The retinal image of targets displayed through a Badal lens system is constant throughout the range of optical distances, eliminating target size as a cue to distance. The targets were driven by servomotors controlled by a NeXT workstation.

Dynamic accommodation was measured with a Tomey Auto Refractometer (Model QR-007 N), modified to measure refraction (sphere, cylinder, and axis) continually (sixteen measurements per second). Each testing session consisted of two staircase inputs over a range from +2D to −7D and a series of six pulse inputs from −1D to −3D and back. Figure 3 shows examples of the recorded responses to a series of pulse inputs and a staircase input.

Data Analysis. The accommodative responses to the staircase inputs were used to determine the lower level of attained accommodation, the upper level of attained accommodation, and the level of tonic accommodation. The highest and lowest level of accommodation were calculated manually from the data; the level of



a. Pulse stimulus and accommodation response.



b. Staircase stimulus and accommodation response.

Figure 3. *Example of pulse and stair stimulus and response.*

tonic accommodation was taken to be the average level of accommodation to the fogged (unclearable) target at +2 D vergence. The accommodative range was defined as the highest level of attained accommodation minus the lowest level.

A series of six pulse inputs was used to determine the subject's average time constant, latency, and amplitude for both the active response (from −1D to −3D) and relaxation response (return from −3D to −1D). The six responses (for each direction) were shifted so that the beginning step portions of the responses were coincident. Previous studies on accommodation dynamics such as that by Shirachi, Liu, Lee, Jang, Wong, and Stark (Shirachi et al., 1978) and Sun and Stark (Sun & Stark, 1986) modeled the accomodation response as a rising exponential equation of the form

$$f(t) = \begin{cases} A_i + A_r\left(1 - e^{-\frac{t-t_l}{\tau}}\right) & \text{if } t \geq t_l \\ A_i & \text{otherwise} \end{cases} \tag{1}$$

was fit to each accommodation response and a decreasing exponential equation of the form

$$f(t) = \begin{cases} A_i + A_r\left(e^{-\frac{t-t_l}{\tau}} - 1\right) & \text{if } t \geq t_l \\ A_i & \text{otherwise} \end{cases} \tag{2}$$

was fit to the relaxation response, where A_i is initial value of the accommodation response, A_r the final magnitude of the step response, τ is the time constant, and t_l is the latency between the change in the stimulus and the onset of the response. In the earlier studies these parameters were fit to the data graphically or by hand; we used the Levenburg-Marquardt nonlinear fit algorithm (Novak, 1992; Press et al., 1988). The latency, time constant, upper level of attained accommodation, lower level of obtained accommodation, and range were determined for each response from the exponential curves. The average and standard deviation of these values were determined excluding any values that were more than ±2 standard deviations from the median (outliers).

As a verification and comparison of these average values, the six responses for each direction were superimposed using the same time basis and then shifted so that the latencies were equal. These six shifted time-series were averaged and plotted along with the exponential curve fit determined from the averaged values excluding outlying data; an example is shown in Figure 4.

3 Results

Results for each test were analyzed in two ways. First, the responses of all the subjects were averaged to see if there were any differences in the group mean and distribution for the pre-TV, post-TV, pre-HMD and post-HMD conditions. Second, the change in the response for each individual subject for the pre- to post-TV, pre- to post-break, and pre- to post-HMD condi-

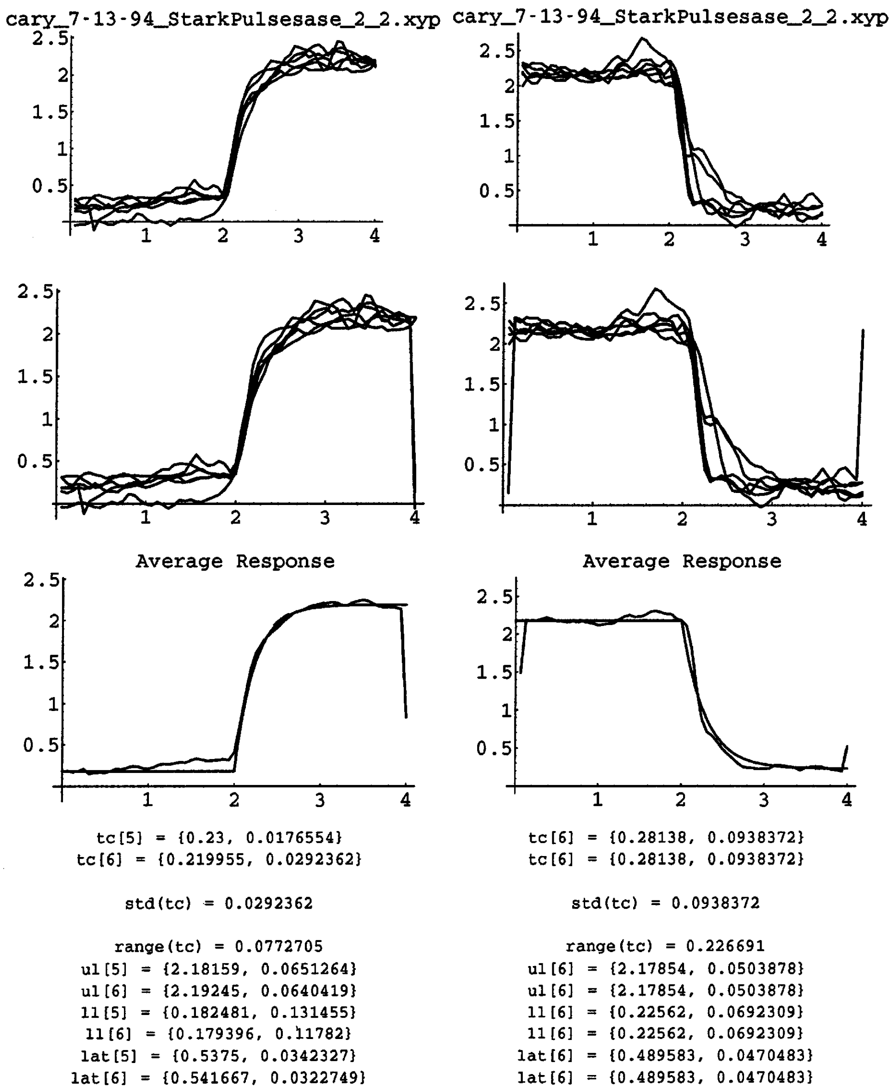
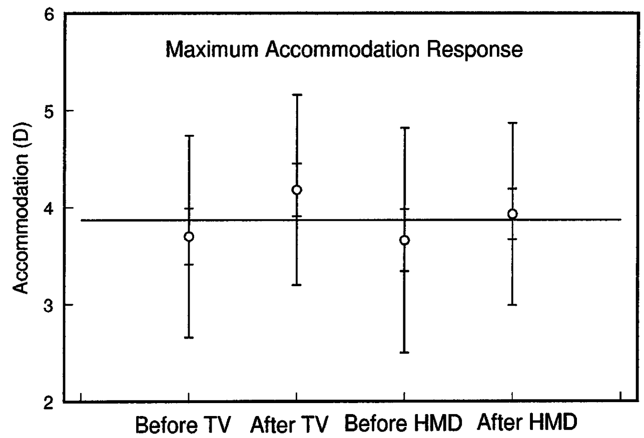


Figure 4. *Ensemble analysis.* Top row: *Accommodation responses to pulse stimulus.* Center row: *Accommodation responses time-shifted so that the computed latencies are equal.* Bottom row: *Mean of time-shifted responses superimposed on the fitted exponential curve. Parameters at the bottom of the figure are: tc[*x*], mean of estimated time constants for* x *respones and their standard deviation; std(tc), standard deviation of tc[6]; range[tc], range of tc[6]; ll[*x*], mean lower level of* x *responses; lat[*x*], mean latency of* x *responses.*

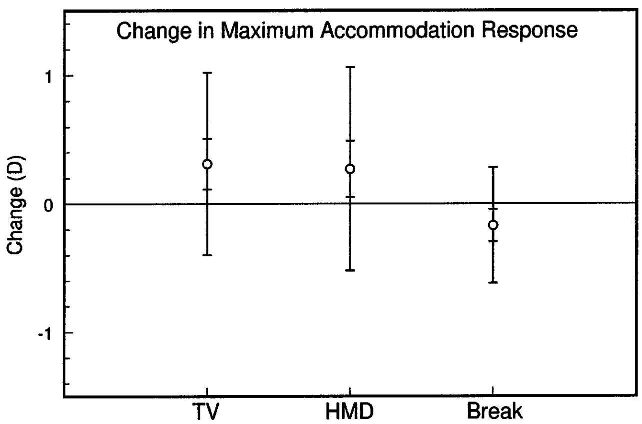
tions were computed, and the mean and dispersion of the distribution across subjects were calculated. In a t-test for $N = 13$ subjects, the probability that true population mean lies between the experimental mean ± 2.179 standard errors is 0.95. Thus, in order to reject the null hypothesis that there is no change, with a probability of greater than 0.95, the mean change in response must be greater than ± 2.179 standard errors.

3.1 Maximum Accommodation Response

The results of the maximum accommodation response measurements are shown in Figure 5. The top graph shows the distribution of the maximum accommodation response across all subjects, and the bottom graph shows the distribution of the change in response.



a. Maximum accommodation response.



b. Change in maximum accommodation response.

Figure 5. *Maximum accommodation response results. Circles show mean values; outer error bars show standard deviation of the data; inner error bars show standard error of the mean.* Upper graph: *horizontal line shows mean maximum accommodation response for all subjects under all conditions.*

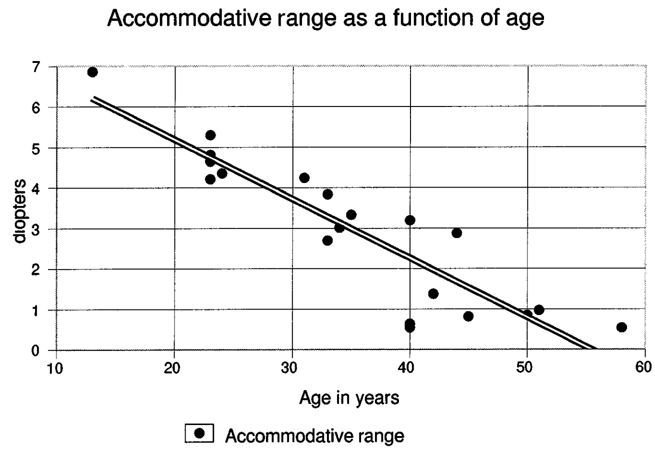


Figure 6. *Maximum accommodation range as a function of age. Equation of the best-fit line is 8.75 − 0.15 age diopters.*

No significant ($p > 0.05$) change was seen in the maximum accommodation response to the staircase stimulus for any of the three conditions.

As Figure 6 shows, there was a strong negative correlation with age, as is expected. The best-fit linear equation to the data gives $8.75 - 0.15$ age diopters as the predicted range of accommodation as a function of age. This compares very well to Sun's (Sun et al., 1988) equation $8.09 - 0.17$ age diopters, measured with a stigmatoscope so depth-of-focus effects are excluded.

3.2 Fogged-target Response

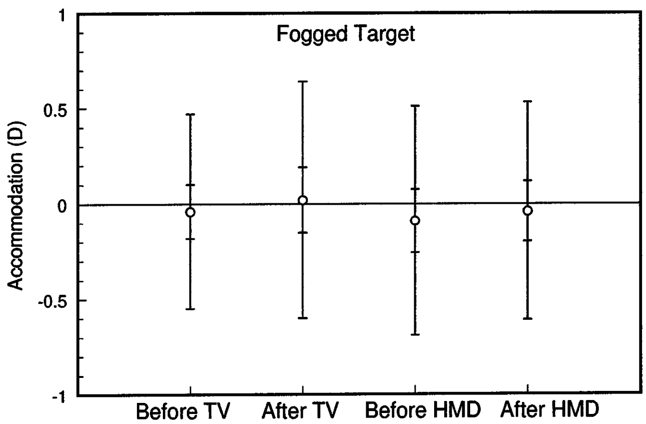
The results of the fogged-target response measurements are shown in Figure 7. The top graph shows the distribution of the fogged-target response across all subjects, and the bottom graph shows the distribution of the change in response. No significant ($p > 0.05$) change was seen in the fogged-target response for any of the three conditions.

3.3 Pulse Responses

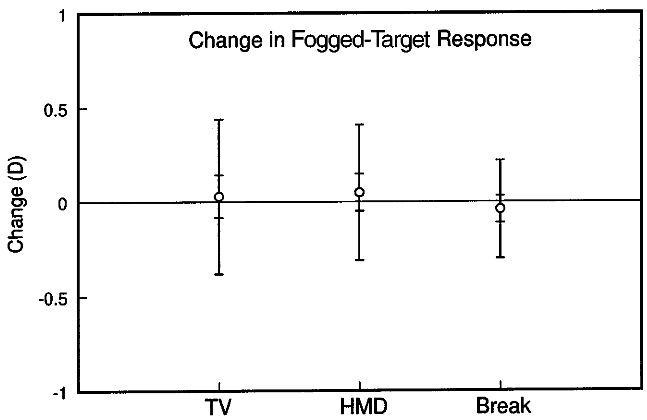
The results of the pulse response measurements are shown in Figure 8. The top graph shows the distribution of the pulse response measurements across all subjects, and the bottom graph shows the distribution of the change in that response. No significant ($p > 0.05$) change was seen in the pulse response for any of the three conditions.

3.4 Pulse Response Latency

The results of the pulse latency measurements are shown in Figure 9. The top graph shows the distribution of the latency measurements across all subjects, and the bottom graph shows the distribution of the change in that response.

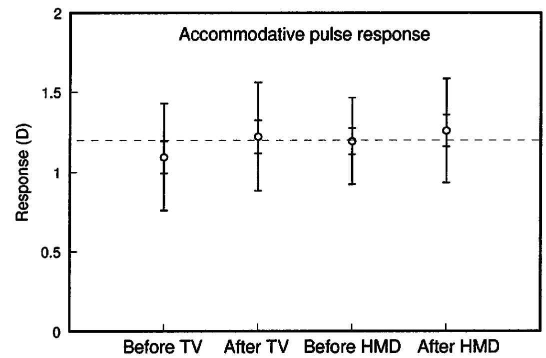


a. Response to +2D (fogged) target.

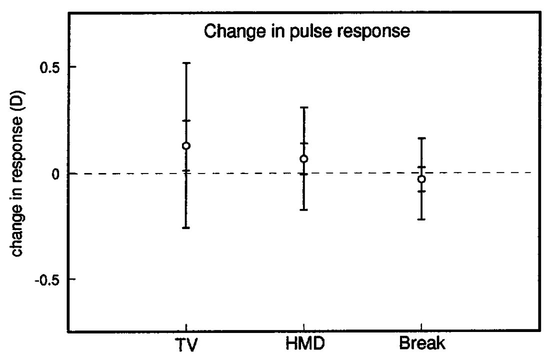


b. Change in fogged-target response.

Figure 7. *Fogged-target response. Circles show mean values; outer error bars show standard deviation of the data; inner error bars show standard error of the mean.*



a. Accommodation pulse response.



b. Change in pulse response.

Figure 8. *Accommodation pulse response. Circles show mean values; outer error bars show standard deviation of the data; inner error bars show standard error of the mean.* Upper graph: *Dashed horizontal line is mean pulse response of all subjects over all conditions.*

No significant change was seen in accommodative latency for any of the three conditions.

A slight increase of 0.1 seconds in relaxation latency, just barely statistically significant ($p < 0.05$) was seen in the HMD condition.

3.5 Time Constant of Accommodation

The results of the time-constant measurements are shown in Figure 10. The top graphs show the distribution of the time-constant measurements across all subjects, and the bottom graphs show the distribution of the change in that response.

No significant change was seen in the time-constant for any of the three conditions.

4 Discussion

Comparing changes in the measured accommodation parameters before and after HMD use with those taken before and after some inert activity, like a one-hour lunch break, allows us to gauge which changes are

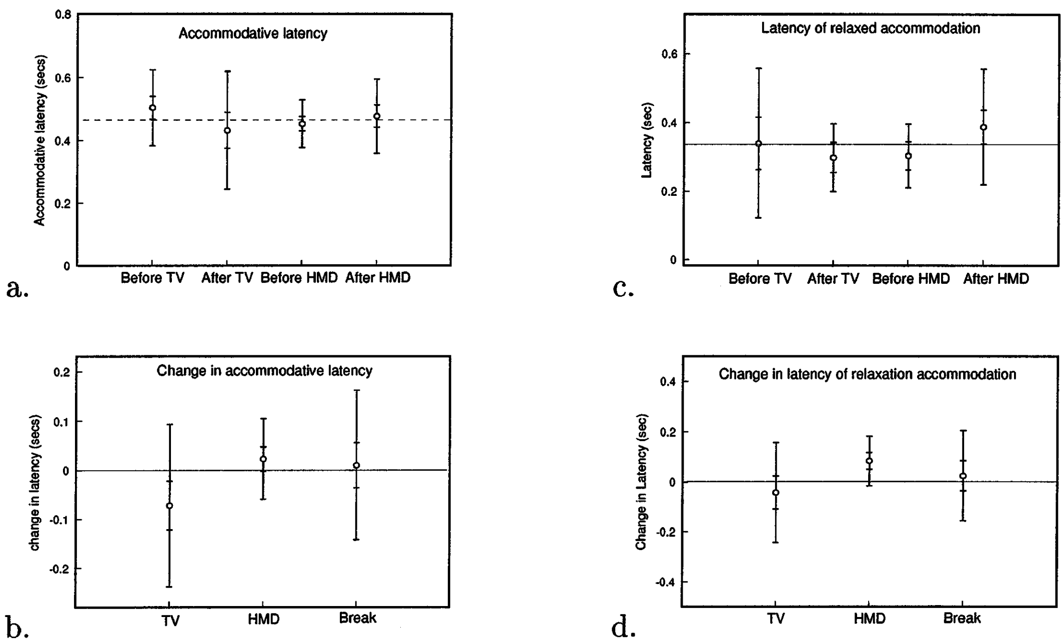


Figure 9. *Latency of accommodation and relaxation. Circles show mean values; outer error bars show standard deviation of the data; inner error bars show standard error of the mean.* Upper graphs: *Horizontal line is mean latency of all subjects over all conditions.*

truly significant and which changes are merely a result of the normal variation in these parameters or normal measurement error and noise.

Likewise, comparison of changes before and after some similar activity, such as viewing a full-length movie on a large screen TV, allows us to gauge whether any change found is common to the activity of watching movies or is specific to HMD viewing.

Only one of the seven measured accommodation parameters showed a statistically significant change over the HMD viewing condition, that of accommodative relaxation latency, which increased by 0.1 seconds on average.

Accommodation and Age. Whenever experimental results fail to exclude the null hypothesis, it is necessary to establish that this is not an artifact of poor experimental technique; for example, if the subjects could not properly see the target we would also expect to see no overall change in the mean responses for the three different conditions. In order to eliminate this possibility, we looked at the change in the accommodation measures as a function of age.

As was mentioned, the maximum accommodation amplitude of the subjects showed a strong and well-known decrease with age, a process called presbyopia and caused by the continuous growth and concomitant increase in thickness of the lens, as well as changes in the chemistry and structure of the lens body and capsule, and changes in the geometry of the lens-zonule relationship (Brown, 1974; Koretz et al., 1984; Stark, 1987). It is also interesting to compare the relationship to age of the other measured parameters with previously published data. Sun et al measured the latency and time constant of accommodation and found no relationship of latency to age and a weak increase in the time constant with age. Our data showed no increase in the time constant of accommodation with age, and a weak increase in the latency of accommodation (see Figure 11). Relaxation latency was nearly constant with age, but the time constant of relaxation showed much more variation, as well as a tendency to increase with age. This last result is interesting in light of two historically competing theories of presbyopia, the now generally accepted Hess-Gullstrand or lenticular theory, which attributes the

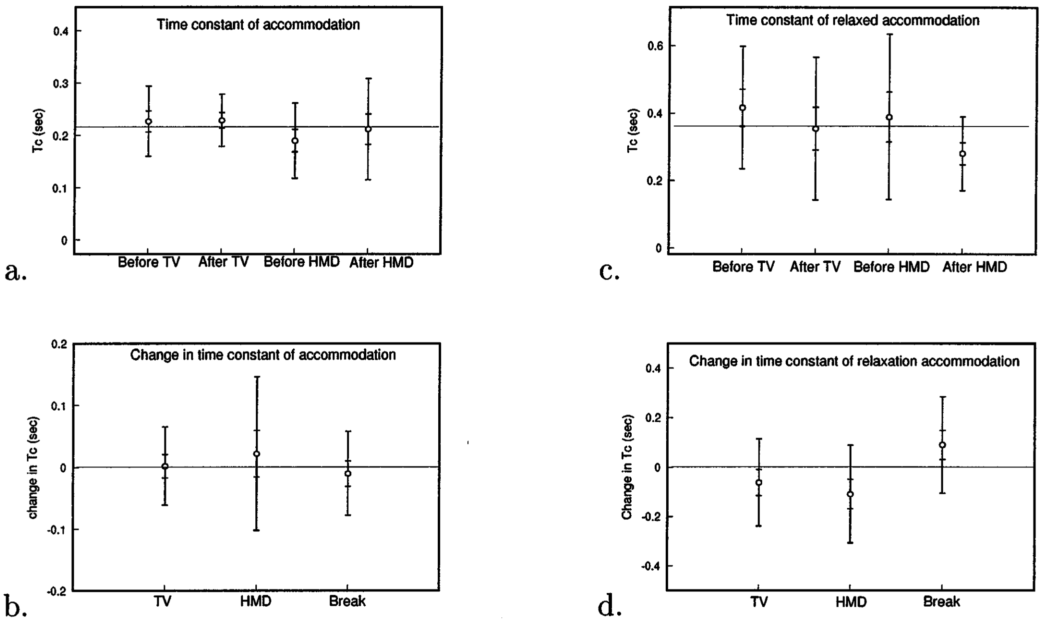


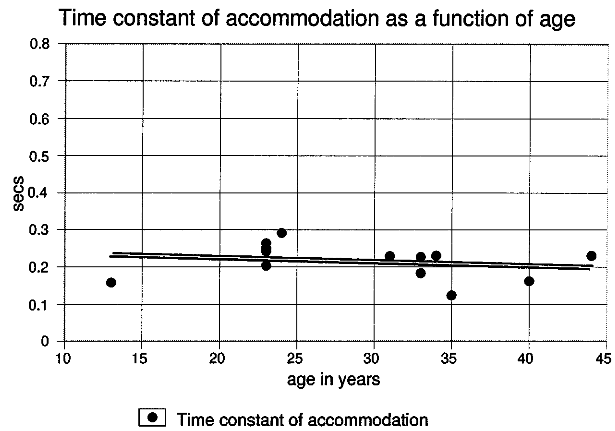
Figure 10. *Time constant of accommodation and relaxation. Circles show mean values; outer error bars show standard deviation of the data; inner error bars show standard error of the mean.* Upper graphs: *Horizontal line is mean time constant of all subjects over all conditions.*

reduction in accommodation amplitude to change in the lens and capsule, and the Duane-Fincham or extra-lenticular theory, which attributes presbyopia to weakening of the ciliary muscle with age.

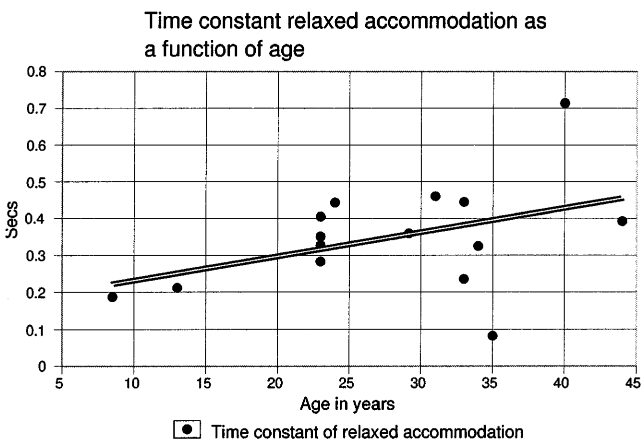
The lenticular theory predicts an increase in the time constant of relaxation, because the stiffer lens (if coupled with a viscosity as is likely) would better resist the tension of the zonules and would take its flattened, unaccommodated shape more slowly, while the extra-lenticular theory predicts an increase in the time constant of accommodation, because of the reduced force of the weakened ciliary muscle. Our data is more consistent with the predictions of the lenticular theory.

No Change with HMD Viewing. Designers of HMDs need to be concerned about visual fatigue or adaptation effects caused by their apparatus. In this study, we were looking for changes in a number of accommodation parameters that would indicate accommodative fatigue or accommodative adaptation. A reduction in maximum accommodation response, or an increase in the latency or time constant of accommodation, would indicate accommodative fatigue. An increase in fogged-target accommodation response, or an increase in the time constant of relaxation, are indicative of adaptation or an increase in tonic accommodation. The results show no significant changes in any of these parameters for any of the three experimental conditions, except for a slight and barely significant ($p < 0.05$) increase in latency of relaxation accommodation for the HMD condition. However, we do not find this compelling. First, there were 21 opportunities (seven accomodation parameters $\times$ three conditions) for this to occur, and there is a one-in-twenty probability that such an occurence will happen by chance. Also, the standard deviation of the relaxation latency for the HMD condition is unusually small compared to those for the TV and break conditions. We would expect the spread to be similar for all three conditions even if the mean differed significantly from zero.

Further Research. Our study was done using a biocular HMD for movie viewing, a simpler situation than with a head-tracking, stereoscopic HMD in a vir-



a. Time constant of accommodation as a function of age.



b. Time constant of relaxation as a function of age.

Figure 11. *Time constants as a function of age.*

tual environment. During movie viewing, the subjects tended to keep their heads still; in contrast, head movement is a fundamental part of the virtual environment experience and introduces further complications. For example, the mass and rotational inertia of the HMD are added to that of the head and interact with the head-movement control system; it is possible that short-term adaptation to the added mass and rotational inertia occurs. Likewise, a stereoscopic display introduces interactions between the accommodation and vergence control systems. Further study of these interactions is needed to determine the short-term effect, if any, on HMD use in virtual environments specifically.

5 Acknowledgements

Our thanks go to Dr. Miyao and Dr. Ishihara for their assistance with the Tomey optometer, also the engineers at Tomey: Eiichiro Nagasaka, Masao Yoshikawa, Susumu Nozawa, and Toshiharu Morino.

Reading Eye Movements: Yun Choi, Ingolf Mertens, M.D.
Optometrist: Jeffrey Hall, O.D.
Optometry Assistants: Heidi Bamberg, Irene Tang, Tina Han, Efrain Mascareno, Deanna Wong, Linda Yee, Carleton Fong, and Russ Ng
Lab Assistant: Sunil Ghandi

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